DISCUSSION ON
"THEORY AND PERFORMANCE OF THE ICONOSCOPE"*

Dr. F. C. Williams (*communicated*): The sections of this paper of greatest interest to me are those dealing with the signal/noise ratio. The exact calculation of noise in such a complicated device is a matter of considerable difficulty, and the authors appear to have made some simplification in the earlier section entitled " Calculation of the sensitivity of the iconoscope." Here they calculate the noise output with reference only to the thermal noise in the coupling resistor and shot noise in the amplifier; they omit the shot noise originating in the iconoscope.

They state on page 109 that "$\overline{V}_N^2 = K_2 fR$, where K_2 is the shot coefficient," but they appear to refer to K_1, the thermal coefficient defined earlier on that page. The present discussion assumes that such is the case.†

Although the beam current does not in fact traverse the resistance R, it appears probable that its shot fluctuations will generate a noise across R relevant to such traversal. Further, the secondary and photo-currents which make up the actual return path of the beam current will probably contribute a further, more or less independent, shot fluctuation across R. Thus if I_b is the beam current, it appears very probable that there will be a fluctuation current traversing R whose mean-square value is

$$\overline{i}^2 = 2A_b I_b e df$$

where A_b is some factor, probably not less than 2, which expresses the extent to which the fluctuations in R exceed those relevant to the passage of a temperature-limited current I_b through R. That A_b will be of the order of 2 seems to be implied in the section relating to electron multipliers; experimental evidence of its probability can be derived from the known properties of tetrode valves. With many such there exists an equilibrium potential for the anode (otherwise than zero) for which the anode current is zero. If the valve be set to operate at this point (by momentarily raising the anode potential above that of the screen) with a condenser and resistance in series connecting the anode and cathode, conditions are closely analogous to those obtaining in the iconoscope. Mr. E. B. Moullin has examined the fluctuations generated in R under such circumstances.‡ He found A_b to be of the order of 2 or more; precise statement is impossible since I_b was unknown and flicker effect was present.

It follows that the signal/noise ratio in the iconoscope is the same as that obtaining in a simple photocell and amplifier having a photo-current $A_b I_b$, the signal photo-current being given an arbitrary r.m.s. value I_0 for the time being. I have discussed this last circuit in a paper recently submitted to The Institution.† It is there shown that with the circuit of Fig. A the (noise/signal)^2 ratio is

$$S^2 = \frac{2A_b I_b e f_0}{I_0^2}\left\{1 + \frac{2kT}{eRA_b I_b} + \frac{AI}{g^2 A_b I_b}\left(\frac{1 + \frac{1}{3}R^2C^2\omega_0^2}{R^2}\right)\right\}$$

where

$A_b I_b$ = mean photo-current.
I_0 = r.m.s. signal current from the photocell.
R = coupling resistance in series with the photocell.
C = interelectrode and stray capacitance from grid to earth.
I = mean anode current of the valve.
A = measure of the depression of shot effect by space charge.
g = mutual conductance of the valve.
$f_0 = \omega_0/2\pi$ = band width to which the amplifier responds;

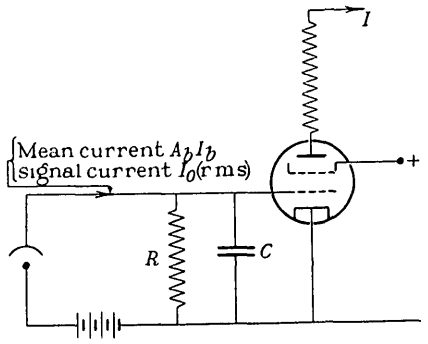

Fig. A

it is assumed that by means of correcting circuits later in the amplifier the response is held constant at all frequencies from zero to f_0 whatever the value of R, and that the response is zero above f_0.

It is evident that, as R is increased, S decreases steadily to the limit

$$S^2 = \frac{2A_b I_b e f_0}{I_0^2}\left\{1 + \frac{AIC^2\omega_0^2}{3g^2 A_b I_b}\right\}$$

thermal noise in R, represented by the second term in the first expression, being then negligible. The term outside the bracket is the (noise/signal)^2 in the photo-current, or, in the case of the iconoscope, the basic limit at the mosaic. The second term inside the bracket represents the fractional extent to which valve noise supplements the basic noise. Valve noise will be negligible if

$$\frac{AIC^2\omega_0^2}{3g^2 A_b I_b} < 1$$

* Paper by V. K. Zworykin, Ph.D., G. A. Morton, Ph.D., and L. E. Flory (see page 105).

† The authors have confirmed that the correction should be made.

‡ *Proceedings of the Royal Society*, 1934, A, vol. 147, p. 100. Actually the condenser was short-circuited in his experiments. Since I is zero this is immaterial; the fluctuation in R will be unaffected by its introduction, provided it is great compared with the anode-cathode capacitance

† "Co-existent Thermal and Thermionic Fluctuations in Complex Networks."

i.e. $$I_b > \frac{AIC^2\omega_0^2}{3g^2A_b}$$

With typical values this reduces to

$$I_b > 0{\cdot}15\ \mu\text{A}.$$

Hence with a high value of coupling resistance ($R = 10^5$ to 10^6 ohms is sufficient) and subsequent frequency compensation, we shall have, if $I_b = 0{\cdot}5\ \mu$A,

$$S^2 \simeq \frac{2A_bI_bef_0}{I_0^2}$$

With the authors' notation, and with $I_0 = FpkA$, this reduces to

$$\frac{1}{N} = S = \frac{\sqrt{(2A_bI_bef_0)}}{FpkA}$$

or $$F = \frac{N\sqrt{(2A_bI_bef_0)}}{pkA}$$

Hence with $N = 10$, $A_b = 2$, and $I_b = 0{\cdot}5\ \mu$A, and their values for the remaining factors,

$$F = 0{\cdot}2 \times 10^{-3}\ \text{lumen/cm}^2$$

as against $0{\cdot}7 \times 10^{-3}$ lumen/cm^2 according to the authors.

Thus the use of high R and subsequent correction should improve the sensitivity by a factor of $3\frac{1}{2}$.

The improvement obtained by this method does not appear capable of attaining such values as are possible with secondary multiplication, for valves are not available for which $\frac{AIC^2\omega_0^2}{g^2Ab}$ is sufficiently low to permit of the advantageous use of much lower values of I_b. But it does appear that the adoption of the system would permit of the more advantageous use of the present commercially-produced iconoscopes.

It is perhaps worth noting that it can be shown from the first equation that the authors' assessment of valve noise is probably rather high; if the same typical valve properties are assumed for $R = 10^4\omega$ as were assumed for high values of R, the value of F is about $0{\cdot}5$ lumen/cm^2